STRANGENESS AND QGP FREEZE-OUT DYNAMICS

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We compare chemical and thermal analysis of the SPS Pb–Pb results at 158A GeV, and present a first chemical analysis of RHIC results. We show how a combined analysis of several strange hadron resonances can be used in a study of freeze-out dynamics.

1 Introduction

Strangeness signature of QGP originates in the observation that when color bonds are broken, the chemically (abundance) equilibrated deconfined state has an unusually high abundance of strange quarks [1]. Considering the possibility that the relatively small size of the plasma fireball would suppress this enhancement, It was shown that when the system size is greater than about five elementary hadronic volumes [2] the physical properties of the hadronic system, including in particular strangeness enhancement, are nearly as expected for an infinite system. Kinetic study of the dynamical process of chemical strangeness equilibration demonstrated that only the gluon component in the QGP is able to produce strangeness rapidly [3]. Therefore strangeness enhancement is today considered to be related directly to presence of gluons in QGP.

The high density of strangeness in the reaction fireball favors formation of multi strange hadrons [4,5], which are produced rarely if only individual hadrons collide [6,7]. In particular a large enhancement of multi strange antibaryons arising with a threshold behavior as function of energy has been proposed as characteristic and nearly background-free signature of QGP [4].

A systematic strange antibaryon enhancement has in fact been observed, rising with strangeness content [8]. Moreover there is now evidence that the enhancement of $\overline{\Xi}$ shows a sudden onset when the number of participating (wounded) nucleons exceeds 50 [9]. Similar results were reported for the Kaon yields by the NA52 collaboration [10]. This threshold behavior arises for volumes which are relatively large and not a result of the smallness of the physical system ('canonical

suppression'[11]), thus arise from opening up of novel reaction mechanisms, as is expected should QGP formation occur.

We also see in the experimental data that particles of very different properties are appearing with identical or similar $m_\perp$-spectra[12]. The symmetry between strange baryon and antibaryon spectra is strongly suggesting that the same reaction mechanism produces Λ and $\overline{\Lambda}$ and Ξ and $\overline{\Xi}$. This is understood readily if a dense fireball of matter formed in heavy ion reactions expands explosively, super cools, and in the end encounters a mechanical instability which facilitates sudden break up into hadrons[13].

Important in the understanding of the strange particle signatures of the QGP phase is the proper determination of the baseline of particle yield expected. The comparison of AA (nucleus-nucleus) results should be always made with the NA (nucleon-nucleus) collision system as the baseline, and in a wide range the value of A should not matter. Experimental results demonstrate that multi strange antibaryons are enhanced against this well defined NA baseline in a pattern expected in QGP hadronization. Yet it has been argued that strangeness signals of QGP are not unique[11], since comparing pp (proton-proton) to pA (proton-nucleus) interactions one observes a change of production pattern of strange particles. Since in these reactions also a change in non-strange particle yields is observed due to isospin selection rules and shadowing, we believe that this line of taught is incorrect.

We report in section 2 that thermal freeze-out occurs at the same condition found in chemical analysis. We also consider the present knowledge about strange hadrons at RHIC. In section 3, we will introduce a method to evaluate the lifespan of the hadronic phase following formation of hadron multiplicity. The idea is to use abundance of unstable resonances which have varying width and to determine fraction which becomes unobservable in consideration of the re-scattering effects.

2 Chemical and thermal freeze-out

2.1 Strange hyperon $m_\perp$ spectra

In recent months experiment WA97 determined the relative normalization of $m_\perp$-distribution for strange particles Λ, $\overline{\Lambda}$, Ξ, $\overline{\Xi}$, $\Omega+\overline{\Omega}$, $K_s=(K^0+\overline{K^0})/2$ in four centrality bins[12]. We have since obtained a simultaneous description of the absolute yield (chemical freeze-out) and shape (thermal freeze-out) of these results[14]. Our strategy is to maximize the precision of the description of the final multi-particle hadron state employing statistical methods. This requires that we introduce parameters which characterize possible chemical non-equilibria, and velocities of matter evolution. These latest results were obtained with two velocities: a local flow velocity v of the fireball volume element where from particles emerge, and hadronization surface (breakup) velocity which we refer to as $v_f^{-1}\equiv dt_f/dx_f$.

We have found, as is generally believed and expected, that all hadron $m_\perp$-spectra are strongly influenced by resonance decays. We assume here that the resonance spectra are not reequilibrated in rescattering. The final particle distribution is composed of directly produced particles and first generation decay products, as no other contributing decays are known for hyperons, and hard kaons. Since the relative contributions of resonances and directly emitted particles are strongly temperature dependent, thermal analysis of hyperons converges to a well defined best temperature and velocities of expansion and hadronization.

We present in Fig. 1 these freeze-out properties. The solid horizontal lines delineate error range of chemical freeze-out analysis we present in subsection 2.2. We see that the thermal freeze-out is consistent with the purely chemical analysis of data that included non-strange mesons and baryons. The value of v_f (top right) is near to velocity of light which is consistent with the picture of a sudden breakup of the fireball.

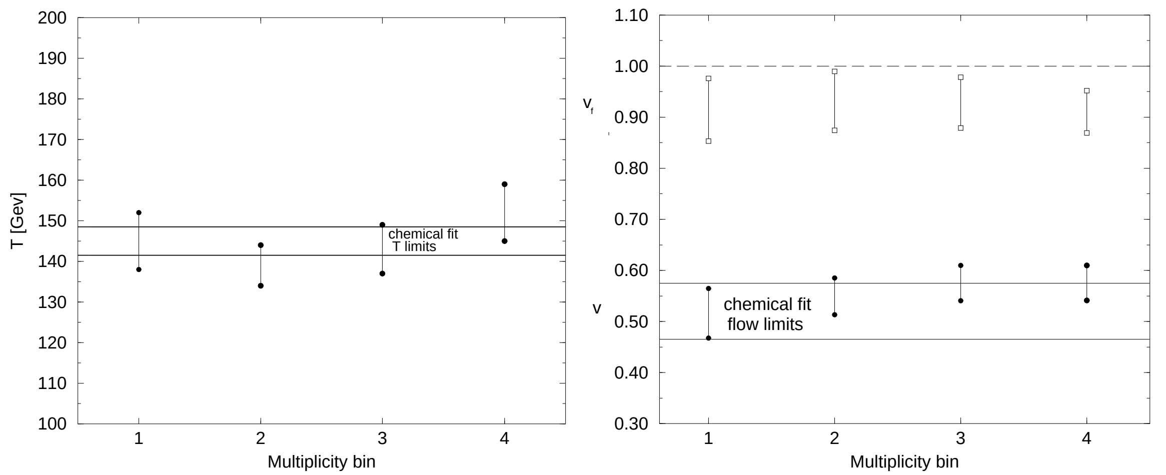

Figure 1: Thermal freeze-out temperature T (left) and flow velocity v (bottom right) and break up (hadronization hyper-surface propagation) velocity v_f (top right) for different collision centrality bins. Upper limit $v_f = 1$ (dashed line) and chemical freeze-out analysis limits for v (solid lines) are also shown.

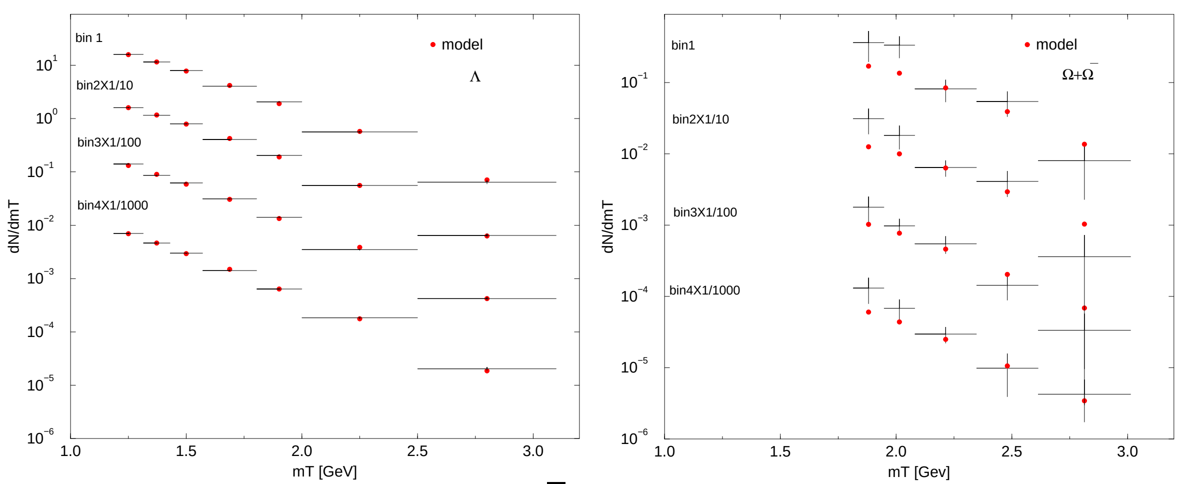

Figure 2: Thermal analysis of Λ (left) and $\Omega + \overline{\Omega}$ (right) m_T spectra for different centrality of collision.

There is no indication in Fig. 1 of a significant or systematic change of T, v, v_f with centrality. This is consistent with the believe that the formation of the new state of matter at CERN is occurring in all centrality bins explored by the experiment WA97. It will be interesting to see if the low centrality 5th bin now studied by experiment WA57 and which shows a different enhancement pattern [9], will also show different thermal freeze-out properties.

We show in Fig. 2 to left Λ-spectra which are most precisely known, and to right $\Omega+\overline{\Omega}$-spectra which are least precisely known. All other (anti)hyperon $m_\perp$-spectra $(\overline{\Lambda}, \Xi, \overline{\Lambda})$ are described as well as we see it in the Λ-spectra. We found that parameters found in the analysis of hyperons and antihypoerons predicted correctly the K_s $m_\perp$-spectra.

Although in the purely chemical fit, we excluded the $\Omega, \overline{\Omega}$ yields due to their anomalous enhancement, we did include their spectra in the thermal analysis. In all four centrality bins for the sum $\Omega + \overline{\Omega}$ we systematically under predict the two lowest $m_\perp$ data points, as is seen in Fig. 2 right panel. This low-$m_\perp$ excess also explains why the inverse $m_\perp$ slopes for $\Omega, \overline{\Omega}$ are reported to be smaller than the values seen in all other strange (anti)hyperons. We note that the 1.5 s.d. deviations in the low $m_\perp$-bins of the $\Omega+\overline{\Omega}$ spectrum translates into 3 s.d. deviations from the prediction of the statistical model chemical analysis.

Table 1: Freeze-out conditions and physical properties of a hadronic matter fireball formed in Pb–Pb interactions at $\sqrt{s_{NN}} = 17.2$ GeV, left column with, and right column without imposed strangeness balance.

	$\mathrm{Pb}\|_v^{s,\gamma_q}$	$\mathrm{Pb}\|_v^{\gamma_q}$
$\chi^2_{\mathrm{T}};\ N;p;r$	2.25; 10; 3; 2	1.36; 10; 4; 2
T [MeV]	150 $\pm$ 3	145 $\pm$ 3.5
v	0.57 $\pm$ 0.04	0.52 $\pm$ 0.055
λ_q	1.616 $\pm$ 0.025	1.625 $\pm$ 0.025
λ_s	1.105*	1.095 $\pm$ 0.02
γ_q	$\gamma_q^{c*} = e^{m_\pi/2T_f} = 1.61$	$\gamma_q^{c*} = e^{m_\pi/2T_f} = 1.59$
γ_s/γ_q	1.02 $\pm$ 0.06	1.02 $\pm$ 0.06
E_f^{in}/S_f	0.163 $\pm$ 0.01	0.158 $\pm$ 0.01
s_f/b	0.68 $\pm$ 0.05	0.69 $\pm$ 0.05
$(\bar{s}_f - s_f)/b$	0*	0.05 $\pm$ 0.05

2.2 Global chemical freeze-out condition at SPS

In our chemical freeze-out analysis to which we compared the thermal results in Fig. 1 there are a few theoretical refinements compared to earlier work [15], such as use of Fermi-Bose statistics throughout, more extensive resonance cascading. In the input data we omit the NA49 $\overline{\Lambda}/\bar{p}$ ratio and update the NA49 ϕ-yields. The total χ^2_{T}, the number of measurements used N the number of parameters being varied p and the number of restrictions on data points r are shown in heading of the table 1. The values imply that our model has a very high confidence level.

In the upper section of table 1, we show statistical model parameters which best describe the experimental results for Pb–Pb data. We show in turn chemical freeze-out temperature, T [MeV], expansion velocity v, the light and strange quark fugacities λ_q, λ_s and light quark phase space occupancy γ_q and the ratio strange to light quark ratio γ_s/γ_q. We fix γ_q at the point of maximum pion entropy density $\gamma_q^c = e^{m_\pi/2T_f}$ since this is the natural value to which the fit converges once the Bose distribution for pions is used.

It is interesting that in the Pb–Pb collisions γ_s/γ_q is so close to unity, the often tacitly assumed value. In this detail the revised analysis differs more than 2 s.d. from our earlier results [15]. Only other notable difference is the prediction for $\overline{\Lambda}/\bar{p} \simeq 0.5$ (not shown in table).

In the bottom section of table 1, we show physical properties of the fireball derived from the properties of the hadronic phase space: E_f^{in}/S_f, the specific energy per entropy of the hadronizing volume element in local rest frame; s_f/b specific strangeness per baryon; $(\bar{s}_f - s_f)/b$ net strangeness of the full hadron phase space characterized by these statistical parameters.

We see, in the bottom of the right column in table 1, that within error strangeness is balanced. In the first column of table 1 we see that imposing exact strangeness balance increases the chemical freeze-out temperature T from 145 to 150 MeV. Insisting on exact balance may be an incorrect procedure since the WA97 central rapidity data, which are an important input into this analysis, are only known at central rapidity. It is likely that the longitudinal flow of light quark content contributes to some mild s–$\bar{s}$-quark separation in rapidity. For this reason we normally consider the results presented in right column of table 1 to be more representative of the freeze-out dynamics.

2.3 First look at RHIC freeze-out

There is now first hadronic particle and strangeness data from RHIC $\sqrt{s_{NN}} = 130$ GeV, presented at QM2001 by the STAR collaboration [17]. We draw the following conclusions from these results;

1. from $\bar{p}/p = 0.6 \pm 0.02 = \lambda_q^{-6}$ it follows $\lambda_q = 1.089$;
2. and hence $\mu_B = 38$ MeV (18% of SPS value) at $T = 150$ MeV. If a hadronization at $T = 175$ MeV applies this value rises to $\mu_B = 44$ MeV.
3. The ratios $\overline{\Lambda}/\Lambda = 0.73 \pm 0.03 = \lambda_s^{-2}\lambda_q^{-4}$ and $\overline{\Xi}/\Xi = 0.82 \pm 0.08 = \lambda_s^{-2}\lambda_q^{-4}$ are consistent within 1.5% with $\lambda_s = 1$, value expected for sudden hadronization.
4. $K^+/K^- = 0.88 \pm 0.06$ is also consistent within error with $\lambda_q = 1.089$.
5. On the other hand the ratio $K^*/\overline{K^*} \simeq 1$ differs from $K/\overline{K}$ significantly. This suggests that $K^*, \overline{K^*}$ yields are influenced at the level of 10% by 'in hadronization' decay product re-scattering in an asymmetric way.
6. Thus $K^*, \overline{K^*}$ should not be used to fix T using the ratios K^*/h^- and $\overline{K^*}/h^-$.
7. The ratio $\bar{p}/\pi = 8\%$ cannot be used to fix T since $\bar{p}$ yield contains undetermined hyperon feed [16].
8. The ratio K^-/π^- does not suffice to fix the temperature: we need at least 3 reliable yield ratios as we must also fix γ_q, γ_s: $K^-/\pi^- = 15\% = f(T)\gamma_s/\gamma_d$.

We conclude that the first RHIC results allow to understand the magnitude of chemical potentials $\mu_s = 0, \mu_b = 38$ MeV, but T and γ_q, γ_s cannot yet be fixed. Given the rescattering phenomena of resonances one cannot do a global analysis without stable strange hadron yields, akin to the situation we have at SPS energy range. Thus the final analysis must await the time these results become available. On the other hand the strong presence of observable resonances in hadronic final state as reported by the STAR experiment implies that hadronization has occurred in a sudden fashion, as has been seen at SPS. Other RHIC results such as correlation analysis, are also strongly suggestive of sudden break-up/hadronization.

The major departure at RHIC from SPS physics is the great strangeness density. We note that:

$$\frac{dN_{K^+}}{dy}|_{y=0} = 35 \pm 3.5\,, \quad \frac{dN_{K^-}}{dy}|_{y=0} = 30 \pm 3\,.$$

Total strangeness ($\bar{s}$) yield depends on unmeasured hyperons. Model calculations suggest more than 20%. Hence:

$$\frac{d\bar{s}}{dy}|_{y=0} > 85 \pm 9\,, \quad \text{compare to} \quad \frac{d\pi^+}{dy} \simeq \frac{d\pi^-}{dy} \simeq 235.$$

Under these conditions calculations suggest that $\bar{s}/b \simeq 8$ (11–12 times greater than at $\sqrt{s_{NN}} = 17.2\,A$ GeV SPS Pb–Pb).

Given this immense strangeness rapidity yield it is very difficult to imagine that among three quarks which coalesce to make a baryon there is no strange quark! Hence we predict that most baryons and antibaryons produced will carry strangeness [16]. Thus non-strange nucleons and antinucleons are strongly contaminated by hyperon decay feed, and at this time the reported nucleon RHIC results cannot be used in order to characterize freeze-out conditions.

3 Resonances and freeze-out dynamics

We consider strange hadron resonance production as probe freeze-out dynamics[18,19]. The $\Lambda(1520)$ abundance yield is found about 2 times smaller than expectations based on the yield extrapolated from nucleon-nucleon reactions [20]. This is to be compared with the enhancement by factor 2.5 of Λ-production. A possible explanation for this effective suppression by a factor 5 is that

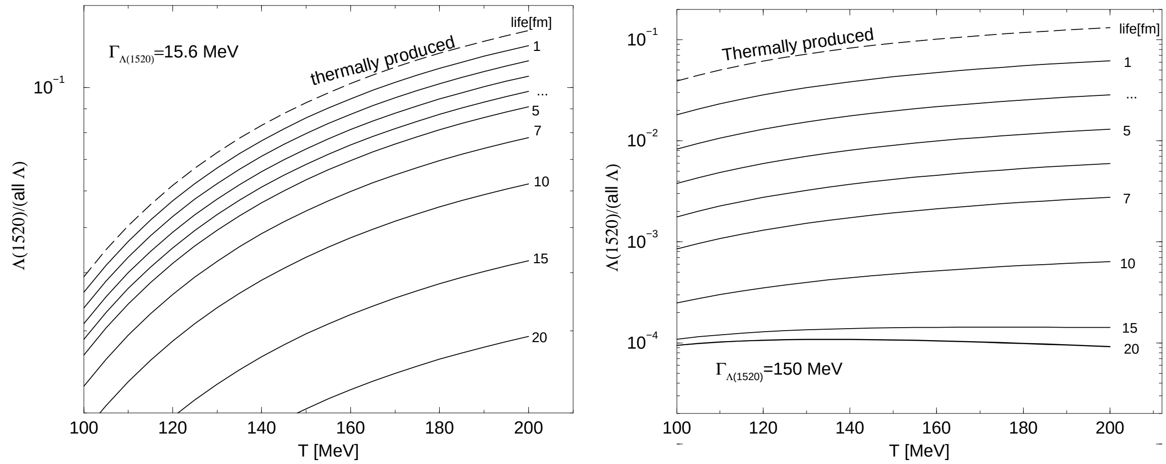

Figure 3: Relative $\Lambda(1520)/(\text{all }\Lambda)$ yield as function of freeze-out temperature T. Dashed - thermal yield, solid lines: observable yield for evolution lasting the time shown (1....20 fm) in an opaque medium. Left: natural resonance width $\Gamma_{\Lambda(1520)} = 15.6$ MeV, right: quenched $\Gamma_{\Lambda(1520)} = 150$ MeV.

the decay products (π, Λ) have re-scattered and thus their momenta did not allow to reconstruct this state in an invariant mass analysis. In a study of the rescattering of the resonance products we found that if the resonance decay occurs in fireball matter, one of the decay products will in general rescatter and thus the resonance will not be observable in the reconstruction of the invariant mass [18].

A back of envelope calculation based on exponential population attenuation suggests that if the observable yield of $\Lambda(1520)$ is reduced by factor 5, the observable yield of $K^*(892)$ with much greater width, $\Gamma_{K^*(892)} = 50$ MeV, should be suppressed by a factor 15. However, both SPS [21] and RHIC experiments [17] report measurement of $K^*(892)$ signal. A possible explanation is that in matter the lifespan of $\Lambda(1520)$ can be quenched in collisions such as $\pi+\Lambda(1520) \rightarrow \Sigma^* \rightarrow \pi+\Lambda$. This is possible since $\Gamma_{\Lambda(1520)}$ is small due to need for angular $L = 2$ partial wave in its decay.

We show in Fig. 3 how quenching impacts $\Lambda(1520)/(\text{all }\Lambda)$ yield: left panel is for the natural width $\Gamma_{\Lambda(1520)} = 15.6$ MeV, right panel is for a width quenched to 150 MeV. NA49 has just reported $\Lambda(1520)/(\text{all }\Lambda) = 0.025 \pm 0.008$ which is barely if at all compatible with the unquenched result, since it implies an extremely long hadronization time of about 20 ± 5 fm/c (depending on freeze-out temperature) which is incompatible with other experimental results. On the other hand, after introduction of a quenched resonance width the experimental result is compatible for all freeze-out temperatures with a sudden hadronization model.

The study of several strange hadron resonances *e.g.* $\Lambda(1520), K^*(892), \Sigma^*(1385)$ $\Gamma_{\Sigma^*(1385)} = 35$ MeV, provides a tool capable of probing conditions at particle freeze-out. We recall that $\Sigma^*(1385)$ decays into Λ and is expected to be produced more abundantly than $\Lambda(1520)$ in a hadronic fireball due to it's high degeneracy factor and smaller mass. How a systematic approach will work is shown in Fig. 4 which shows relative yield of one resonance as function of another, here presented for their natural widths. As indicated from top to bottom in the grid, the lifespan in matter increases, while from left to right the temperature of chemical freeze-out increases.

4 Summary and conclusions

To close we look at a few highlights of our report. Our thermal freeze-out analysis confirms that CERN-SPS results decisively show interesting and new physics, and confirms the reaction picture of a suddenly hadronizing QGP-fireball with both chemical and thermal freeze-out being the same. Thermal freeze-out condition for strange hadrons $(\mathrm{K}_s^0, \Lambda, \overline{\Lambda}, \Xi, \overline{\Xi})$ agree within error

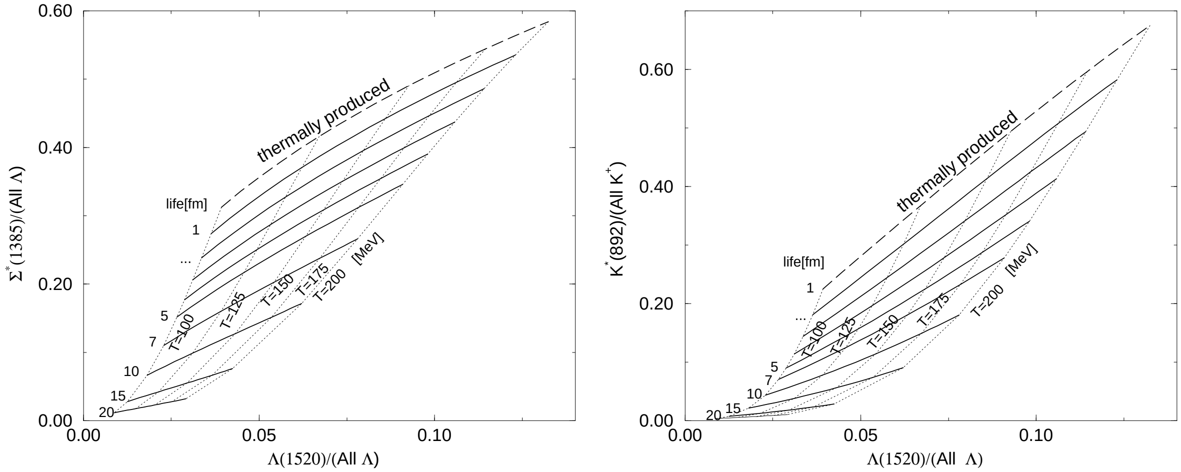

Figure 4: Dependence of the combined Σ^*/(all Λ)with $\Lambda(1520)$/(all Λ) (left) and $K^*(892)$/(all K) with $\Lambda(1520)$/(all Λ) (right) resonance production on the chemical freeze-out temperature and hadron matter lifetime.

with chemical freeze-out and we have confirmed the freeze-out temperature $T \simeq 145\,\mathrm{MeV}$.

We were able to determine the freeze-out surface dynamics and have shown that the breakup velocity v_f is nearly velocity of light, as would be expected in a sudden breakup of a QGP fireball. We found that the experimental production data of $\Omega+\overline{\Omega}$ has a noticeable systematic low-$p_\perp$ enhancement anomaly present in all centrality bins. This result shows that it is not a different temperature of freeze-out of $\Omega+\overline{\Omega}$ that leads to more enhanced yield, but a soft momentum secondary source which contributes almost equal number of soft $\Omega+\overline{\Omega}$ compared to the systematic yield predicted by the other strange hadrons.

We have presented in section 3 results on strange hadron resonance production and argued that a study of several resonances with considerably different physical properties must be used in a study of freeze-out dynamics of QGP. Strange resonances are easier to explore, since their decay involve rarer strange hadrons and thus the backgrounds are smaller. Moreover, the detectability of the naturally wide non-strange resonances is always relatively small, except if (very) sudden hadronization applies. For this reason it will be quite interesting to see if $\Delta(1230)$ can be observed at all, as this would be only possible if chemical and thermal freeze-out conditions are truly coincident.

This discussion of how resonances help to understand the hadronization dynamics is a beginning of a complex analysis which will occur in interaction with experimental results. We saw that observable strange resonance yields can vary widely depending on conditions which should allow a detailed study of QGP freeze-out dynamics. We believe considering $\Lambda(1520)$ result that in-matter resonance lifetime quenching is significant.

Acknowledgments

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